Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution

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LONG-TERM GOAL

The long-term goal is to develop a new generation of wave prediction capability, which is called **SNOW** (**s**imulation of **n**onlinear **o**cean **w**ave-field), for the evolution of large-scale nonlinear ocean wavefields using direct phase-resolved simulations. Unlike the phase-averaged approaches, SNOW models the key physical mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

OBJECTIVES

The specific scientific and technical objectives are to:

1. Continue to develop and improve physics-based phenomenological modeling for wind forcing input and wave breaking dissipation.

2. Continue to speed up the computational algorithm underlying SNOW simulations on massively-parallel high-performance computing (HPC) platforms. To extend the current capability to spatial-temporal scale that would enable more direct comparisons to phase-averaged models and meso-scale observations.

3. Extend current capabilities to handle high sea states and very steep local waves while maintaining near linear SNOW operational count.

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Center for Ocean Engineering,Department of Mechanical Engineering,Cambridge,MA,02139**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

4. Extend SNOW simulations to allow more general initial/boundary conditions based on spectral characteristics or hybrid (point and/or whole field) wave measurements. Investigate and understand uniqueness and compatibility issues of such input to phase-resolved reconstruction of directional broadband wavefields.

5. Characterize and quantify the effects of noise, uncertainty, incompleteness, and incompatibility in hybrid wave data on phase-resolved wavefield reconstruction and prediction.

6. Perform direct validation and quantitative cross-calibration of SNOW simulations with phase-averaged wave model predictions and field/laboratory measurements.

7. Extend SNOW to general finite water depth by including effects of changing bathymetry, variable current and fluid stratification.

APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the evolution of large-scale nonlinear ocean wavefields. SNOW is fundamentally different from the existing phase-averaged models in that, under SNOW, key physical mechanisms such as wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation are modeled, evaluated and calibrated in a direct physics-based context. In SNOW, detailed phase-resolved information about the wavefield is obtained, from which the statistical wave properties can also be derived.

SNOW is based on an extremely efficient high-order spectral (HOS) approach for direct computation of nonlinear ocean wavefield evolution. HOS is a pseudo-spectral-based method that employs Zakharov equation and mode-coupling idea and accounts for nonlinear wave-wave, wave-current, and wave-bottom interactions to an arbitrary high order (M) in wave/bottom steepness. This method obtains exponential convergence and (approximately) linear computational effort with respect to M and the number of spectral wave/bottom modes (N). SNOW is an ideal tool for phase-resolved prediction of realistic ocean wavefield evolution.

By incorporating point and/or whole field wave measurements into the simulations, SNOW provides a capability of reconstructing and forecasting nonlinear evolution of phase-resolved ocean wavefields. The objective of wave reconstruction is to obtain detailed specifications (including phase) of a nonlinear wavefield, which matches given (directly or remotely sensed) sensed wave data or specified wave spectrum. Nonlinear wave reconstruction is achieved based on the use of optimizations with multiple-level (theoretical and computational) modeling of nonlinear wave dynamics. Using the reconstructed wavefield as initial conditions, SNOW simulation would provide a deterministic forecasting of the phase-resolved wavefield evolution. The validity of the nonlinear reconstruction and forecasting methodology has been systematically verified against laboratory measurements and synthetic wave data for both long- and short-crested irregular wave-fields (Wu 2004; Yue 2008).

SNOW computations can now be routinely performed for nonlinear ocean wavefields in an domain of $O(10^{3\sim4})$ km^2 with an evolution time of $O(1)$ hours. Such large-scale SNOW simulations are normally performed on advanced high-performance computing platforms using up to $O(10^3)$ processors (Xiao, Liu & Yue 2009, 2010) under our DoD challenge project: "Large-Scale Deterministic Predictions of Nonlinear Ocean Wavefields".

WORK COMPLETED

The project started at late April, 2010. In the last five months of FY2010, we focused on the research in support of extension of SNOW to non periodic boundary conditions and very steep waves. We also developed new algorithm to improve the resolution in radar inversion data for wave measurements. In addition, we also applied SNOW computations to obtain comparisons with other model predictions and field measurements.

- *Development of a new algorithm for radar inversion data*: We developed a new algorithm for the improvement of radar data inversion associated with the distance. The algorithm is tested and validated using the HiRes 2010 field wave measurements (with Wamos radar).

- *Modeling of wind forcing input*: We continued the development, validation, and calibration of the phenomenological wind input modeling by direct comparisons with HiRes 2010 field measurements.

- *Development of an efficient algorithm for steep waves*: We continued to develop and apply a highly efficient computational algorithm, so-called pre-corrected FFT method (PFFT), for fully-nonlinear simulation of very steep waves. This approach is based on the boundary-element method with the use of the fast Fourier transform technique to accelerate the evaluation of influence coefficients (Yan & Liu 2010a, b). With PFFT, the requisite computational effort in solving the nonlinear boundary value problem is reduced from $O(N^{2\sim3})$ to $O(N \ln N)$, similar to that in HOS. Integration of this algorithm into SNOW would extend the capability of SNOW to fully-nonlinear simulations of extreme wave dynamics and high sea states with the high computational efficiency retained.

- *Investigation of stratified fluid and bottom topography effects upon wavefield evolution*: We extended and applied SNOW simulations to littoral zones including stratified fluid, shoaling, and bottom topography effects. We investigated the high-order resonant interactions of three-dimensional surface waves with bottom ripples, which help understand the complexity of wavefields in littoral zones, in particular, the generation of infragravity waves (Alam, Liu & Yue 2010).

- *Speedup and applications of SNOW simulations*: We constantly improved the computational speed, scalability and robustness of the SNOW code on HPC platforms for the simulation of large-scale ocean wavefield evolutions. We applied large-scale SNOW computations to investigate the characteristics of statistic quantities of nonlinear ocean waves and to understand the generation mechanisms and statistical features of rogue waves in deep ocean.

RESULTS

The key result is the development of a new algorithm that significantly improves the resolution of radar data inversion in ocean wave measurements. In this algorithm, we integrate the nonlinear wave reconstruction (with SNOW) into the process of radar data inversion. It scales back the signal that is lost as the distance from the radar increases. This algorithm is tested and validated with the HiRes 2010 field wave measurements (by Wamos radar). Figure 1 shows the comparison between the inversion data and the SNOW prediction. At t=0, the radar inversion data is used to initialize the

SNOW simulation. Then the SNOW prediction of the wave-field at t=3T (T=6 s) is compared to the radar measurement at t=3T. It is seen that they do not compare well at t=3T even though they compare perfectly at t=0. This indicates that some information of the wavefield is lost in radar measurement. Figure 2 shows the similar comparison between the SNOW prediction and the inversion data that is corrected by the algorithm developed in this study. It shows that the comparison between the SNOW prediction and the radar wave measurement at t=3T is much improved.

IMPACT/APPLICATIONS

This work paves the way toward the development of a new generation of wave prediction tool using direct phase-resolved simulations. It augments the phase-averaged models in the near term and may serve as an alternative for wave-field prediction in the foreseeable future.

RELATED PROJECTS

This project is related to the project entitled "High-Resolution Measurement-Based Phase-Resolved" (N00014-08-1-0610). The present project focuses on the development of advanced algorithms and physics-based modeling for the prediction of large-scale ocean wavefield evolution while the related project focuses on the practical application of the wave reconstruction and prediction capability to realistic ocean environments.

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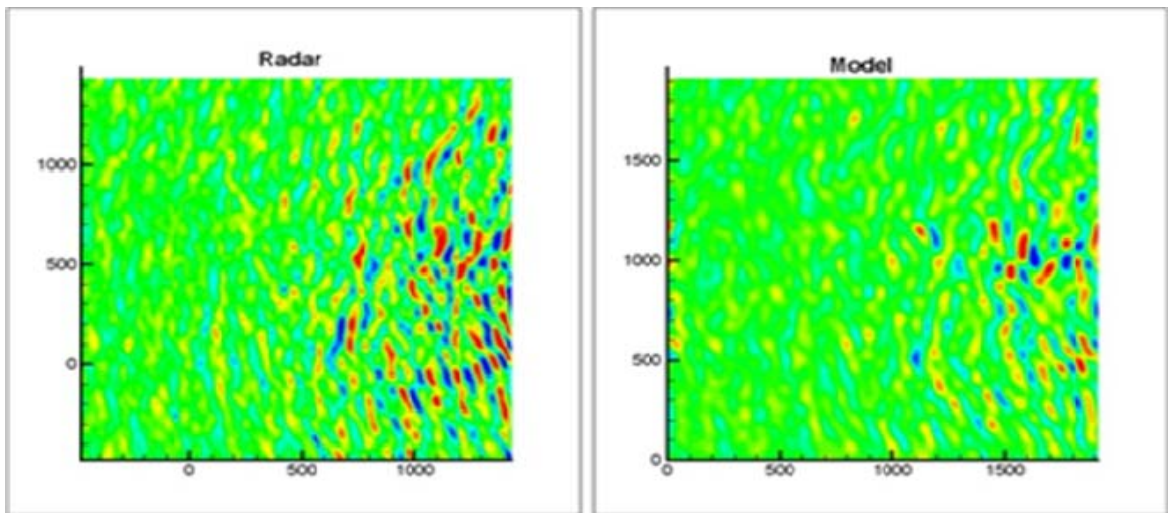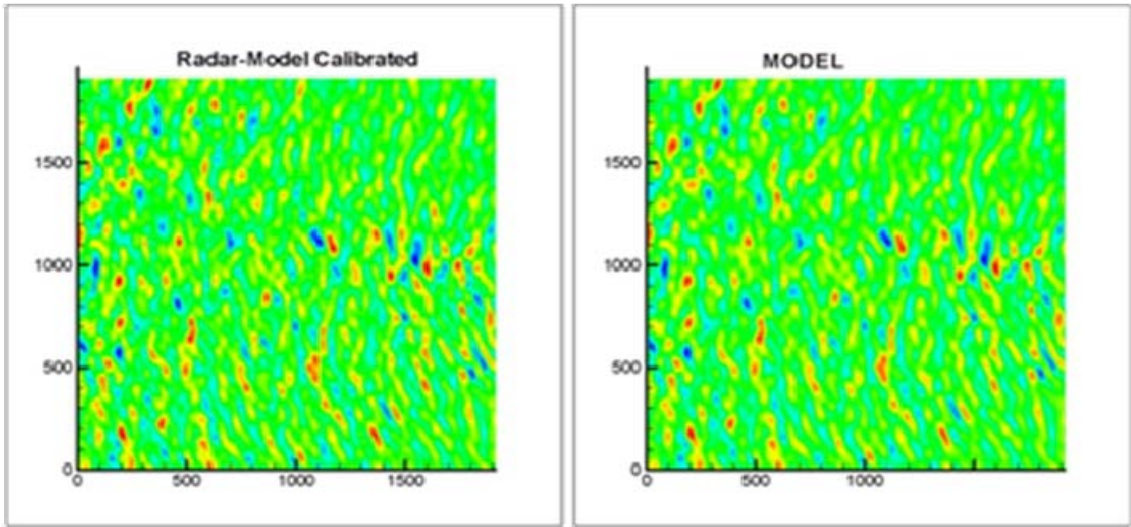
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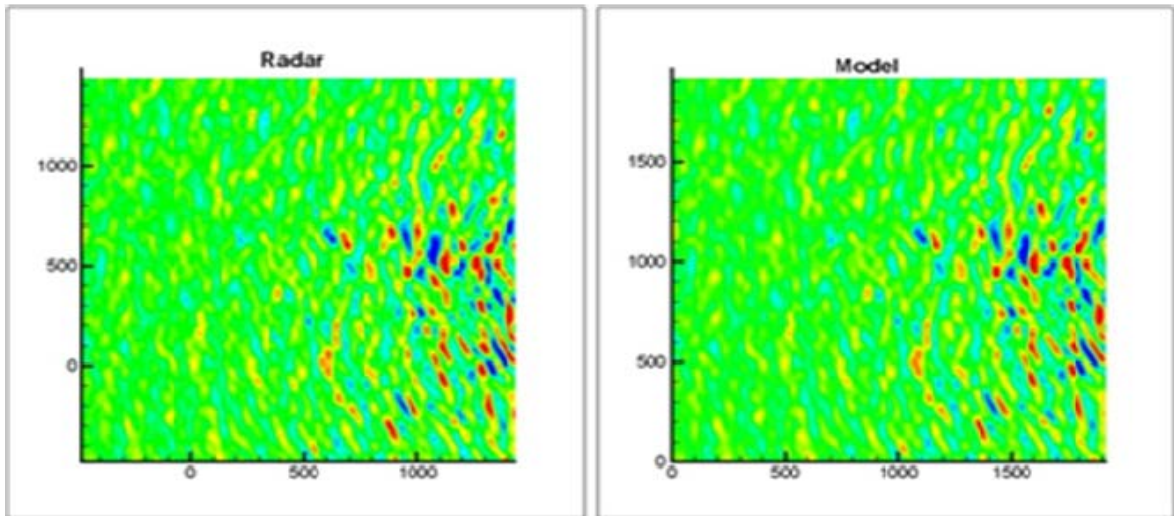
t = 1T, T=6s

Figure 1: Comparison between radar inversion
(June 7ᵗʰ, 2010, from FLIP) (non-scaled) with model (SNOW) prediction.
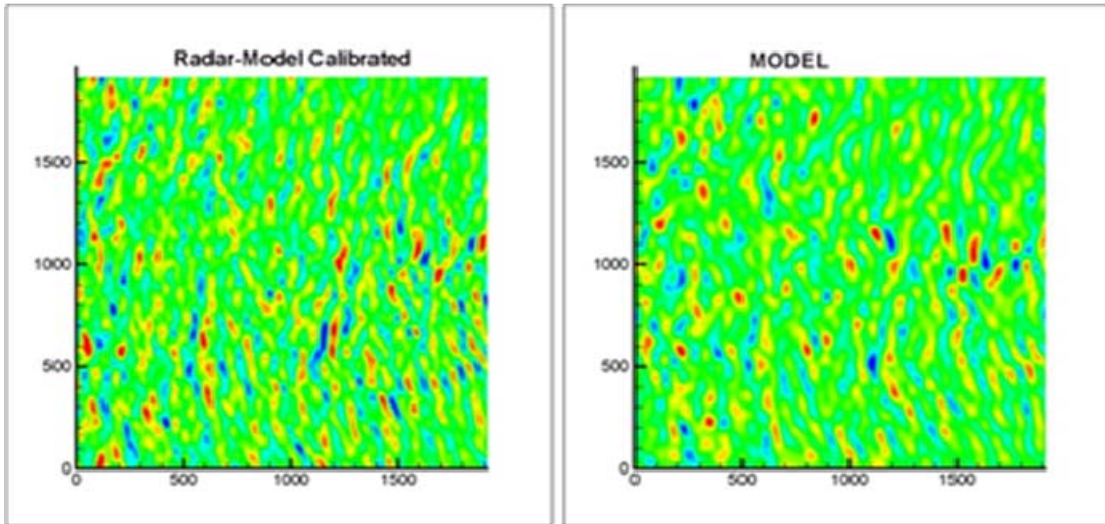
t = 0T, T=6s

t = 1T, T=6s

Figure 2: Comparison between radar inversion (June 7ᵗʰ, 2010, from FLIP) (scaled by the new developed algorithm) with model (SNOW) prediction.